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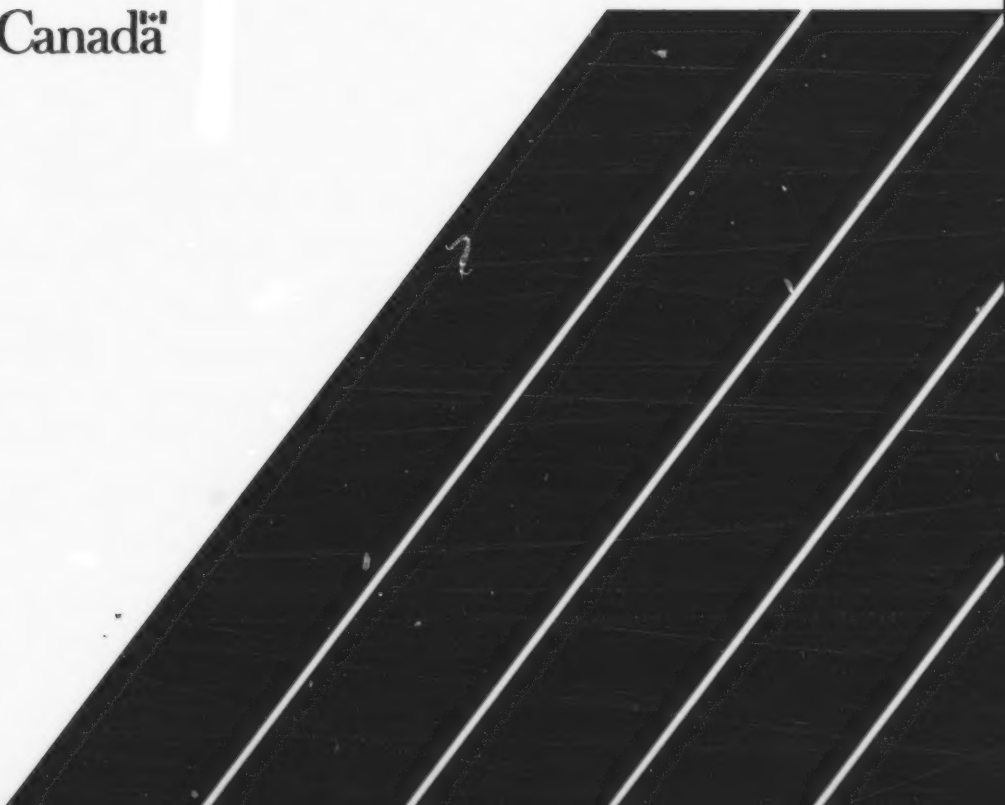
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Fabrication of Experimental Gas Metal Arc and Shielded Metal Arc Weldments on Carbon-Manganese Steel Plates

Final Report by: Fleet Technology Ltd.

DSS File No.003SQ.23440-9-9109

CANMET Scientific Authority: Dr. R.J. Brigham

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CANMET



**FABRICATION OF EXPERIMENTAL
GAS METAL ARC AND
SHIELDED METAL ARC WELDMENTS ON
CARBON MANGANESE STEEL PLATES**

by
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Work on this project was conducted under the auspices of the Department of Energy, Mines and Resources. (PERD)

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EXECUTIVE SUMMARY

Fifty four panels have been welded using shielded metal arc & pulsed gas metal arc welding process, and delivered to Metals Technology Laboratories for further seawater corrosion testing. The shielded metal arc weldments incorporated weld metal composition, heat input and weld bead sequence/temperbead technique as the variables. For the pulsed gas metal arc weldments, the wire and shielding gas composition were the main variables.

SOMMAIRE EXECUTIF

On a réalisé la soudure de cinquante quatre panneaux à l'arc de métal sous protection à impulsion de gaz. Les panneaux ont été livrés à "Metals Technology Laboratories" pour compléter les essais de corrosion par l'eau de mer.

Les soudures à l'arc de métal sous protection incorporées une composition de métal de soudure, de la chaleur et suivant une technique de cordon de soudure en sequence/du cordon tremper comme variables.

Les principaux variables du soudure de métal à pulsation de gaz étaient la composition du fil et le gaz utilisé.

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1.0 INTRODUCTION

Fleet Technology Ltd. has produced fifty four weldments to be used for weld zone sea water corrosion studies at Metals Technology Laboratory, CANMET. This report provides a description of the corrosion study objectives, weld procedure development methodology, and all the details necessary for the identification of supplied welded panels. Two welding processes were used to produce the panels and these will be dealt with separately since the program objectives vary for each.

2.0 TECHNICAL BACKGROUND

2.1 Shielded Metal Arc (SMAW) Weldments Using Strategic Bead Placement and Temperbead Weld Deposition Techniques

Shipbuilding steels for icebreakers must possess adequate notch toughness to guard against unstable fracture in the cold arctic environment. From the standpoint of steel design, such steels typically contain approximately 1.4 wt % manganese (Mn) in order to meet CVN toughness requirements at -40°C (for EH36 steel) or below. However, it is well established (1, 2) that above approximately 1.1 to 1.2% Mn, the heat affected zone (HAZ) corrosion susceptibility increases significantly (see Fig. 1). Thus, one has to accept either preferential HAZ corrosion attack and the associated stress concentration effects, or high weld metal corrosion rates which, in turn, may necessitate more frequent repairs.

While EH36 steels have been designed with nominal 1.2% Mn, and supplied to the Canadian Coast Guard (3), a recent study (4) found that even for such a steel, its virgin heat affected zone (at approximately 1.5 kJ/mm heat input), unaltered by the thermal cycle of subsequent passes, and the weld metal could only be matched for "moderate" corrosion susceptibility and not in the desired "negligible" region. The heat affected zone corrosion susceptibility for virtually all weldments was lower for HAZ's associated with the first capping pass and this was attributed to the reheating effect of the second and subsequent passes in the same layer. It was therefore inferred that optimum design of welding procedures for ship steels containing more than approximately 1.2% Mn and exposed to the seawater environment must incorporate some approach which reheats base metal heat affected zones, be it by strategically placing surface weld beads during multipass welding, furnace stress relief or normalizing, or some other technique. (It should be noted that stress relieving or normalizing are not economically viable for ship construction and, in practice, one would have to rely upon a suitable weld bead placement approach.)

Secondly, it is also quite apparent from Figure 1 that the heat affected zones formed at higher heat inputs also have higher seawater corrosion resistance. This is to be expected since both reheating weld bead techniques and high heat input have the effect of, qualitatively speaking, softening the microstructure, and perhaps having a lower amount of constituents such as retained austenite or martensite islands. However, once again, the heat input in practice can be varied over a limited range only with the shielded metal arc welding process (usually by changing the electrode diameter).

The objective for the SMAW panels produced in the program, is therefore to establish, after subjecting suitably extracted specimens to corrosion tests, if the strategic bead placement at two different heat input levels (1.0 and 2.5 kJ/mm) can be instrumental in significantly reducing the seawater HAZ corrosion in steels with different manganese levels (1.2 and 1.6 %) and employing weld metals of various chemistries.

Reference panels were also produced using similar heat inputs and common deposition sequences, as used in previous CANMET studies. Temperbead procedures based on established techniques have also been developed and applied to produce panels representing high and low heat input procedures.

2.2 Pulsed Gas Metal Arc Weldments

Weldments fabricated using SMAW, SAW and FCAW have already been examined for their seawater corrosion resistance using the CANMET tank test, and evaluation of P-GMA weldments fabricated in this program will make available a more comprehensive data base for all the conventional arc welding processes and indicate if the P-GMA welds are more or less susceptible to preferential corrosion than those made by other processes. There may be some systematic effects due to the higher residual copper content of GMAW deposits (beneficial) or their usually higher Mn and Si contents (deleterious).

Equally important, the GMAW process offers the ability to change the weld metal oxygen content without significantly changing the deposit chemistry otherwise. This could be an important factor based on the results of a recent investigation carried out on behalf of the Canadian Coast Guard (5). In this study, it was observed that in submerged arc weldments made using the same wire but different fluxes (different basicities and therefore different weld metal oxygen contents), basic fluxes (lower weld metal oxygen) had higher weld metal seawater corrosion susceptibility. In the present program, two shielding gases were employed e.g. Ar - 5% CO₂ and Ar - 20% CO₂. For the program wires specified, these shielding gas mixtures should typically lead to oxygen levels that are approximately 200 ppm, and 300 ppm respectively. Weldments have been produced with six different GMAW wires and the two steels used for SMA welds, to also evaluate the effect of weld metal chemistry on its seawater corrosion resistance for two different base material Mn levels.

3.0 EXPERIMENTAL

3.1 Materials

The chemistry of the two steels used for the fabrication of weldments is shown in Table I. The steel designated as "1" has a high Mn content of 1.62%. The 35mm thick steel was produced by the on line accelerated cooling processes and was used for one of the icebreakers built at Versatile Pacific Shipyard. On account of its high Mn content, the steel can be expected to show high HAZ corrosion rates though to some extent it may be mitigated by the presence of 0.6% Ni and .25% Cu in the steel.

The second steel ("2"), 25mm thick, has a Mn content of 1.23%, close to the 1.2% deemed suitable from a HAZ corrosion resistance point of view. Ideally, the steel should have been normalized to meet the grade "EH36" requirements. However, due to time constraints, it was decided to use the steel in the "as hot rolled" condition since corrosion is expected to be primarily a function of the chemistry (Mn content), and any effects due to different microstructure are anticipated to be of secondary importance.

For shielded metal arc weldments, the four electrodes employed were:

E 7018 (LA7018)	:	3.2 and 5.0 mm Φ
E 7018-1 (LA18+)	:	3.2 and 5.0 mm Φ
E 8018-C1	:	3.2 and 5.0 mm Φ
E7018-RCR	:	3.2 and 4.0 mm Φ

The main difference between the E7018 and E7018-1 electrodes is in their Mn contents. The weld deposit from E7018 electrodes typically has 1.0% Mn, whereas that from E7018-1 would have higher Mn content, in the range 1.2 to 1.6%. As a result, the E7018-1 deposits are expected to have better toughness but inferior weld metal corrosion resistance. The E8018-C1 (2.5% Ni) and E7018-RCR (nominally 0.6% Cu, 0.6% Ni) are known to provide deposits with much better seawater corrosion resistance.

The electrode diameters used were 3.2 and 5.0 mm except for the E7018-RCR electrodes, where due to the unavailability of the 5.0 mm Φ electrodes, 4.0 mm Φ electrodes were used for the high heat input weld beads.

All electrodes were procured from Canadian Liquid Air.

The typical composition of the six GMAW wires, nominally 1.2 mm Φ , is shown in Table II. Weldments were produced using two shielding gases, viz., 95% Ar - 5% CO₂, and 80% Ar - 20%CO₂ for each base material steel-wire combination.

3.2 Fabrication of Shielded Metal Arc Weldments

3.2.1 Heat Input (SMAW)

Two heat inputs were used for each electrode type and deposition sequence to represent low and high values within range of practical use. These were 1.0 and 2.5 kJ/mm, respectively. Similar nominal heat input values were also used for fill passes in temperbead welding procedures after applying a butter layer deposited at 50% of the nominal heat input value, e.g. the butter layer heat input was .5 kJ/mm for the 1.0 kJ/mm, and 1.25 kJ/mm for the 2.5 kJ/mm fill procedure, respectively. An electrode guide mounted on a moving carriage was used to control arc travel speed and maintain target heat input values during all shielded metal arc welding.

The low and high heat input welds were deposited in rectangular grooves, machined into the ≈ 750 mm long plates.

3.2.2 Bead Sequences (SMAW)

Four separate bead sequences were used for SMAW weldments. Sequence #1 was designed to reheat surface layer toe regions with a 50% bead overlap (Figure 2a). Weld deposition, therefore, alternated from one side to the other positioning the final weld beads in the centre of each layer. Electrode type was a variable for sequence #1 weldments only. For all other sequences, only E8018-C1 electrodes were used.

Sequence #2 procedures were applied for comparison against E8018-C1 sequence #1 panels for both high and low heat input. Sequence #2 welds were deposited in a right to left progression using a target 50% overlap (Figure 2b). This technique, typical of weldments evaluated in past CANMET programs, would therefore have one surface layer HAZ in a similar condition as both sides of sequence #1 panels, and one HAZ unreheated, i.e. in the as-deposited condition.

Sequences #3 and #4 were "temperbead" procedures wherein the objective was to recrystallize the HAZ at weld toes by carefully placing weld beads. This was achieved by depositing a thin butter layer of weld metal (50% of the nominal heat input) on the full machined groove surface followed by a layer of nominal heat input (1 and 2.5 kJ/mm) weld beads deposited using larger diameter electrodes (Figure 2c). Recrystallizing the HAZ due to the butter layer in the base material, by the temper bead fill layer was the principal objective during procedure development and test panel production. Sequence #3 and #4 varied only in the target "offset" distance which is the distance between the temperbead edge and the HAZ it is attempting to reheat.

The identification scheme used and the full SMAW test matrix are described in Table III. Details of each weld sequence and the welding parameters used are presented in Appendix A. A representative macrosection of each procedure is also presented in Appendix A following each welding procedure sheet.

3.2.3 Procedure Development

(a) Strategic Bead Placement Procedures (Sequences #1 and #2)

Procedure development for sequences #1 and #2 was straight forward where optimum currents were selected and travel speeds adjusted to provide the required heat inputs for 1.0 kJ/mm and 2.5 kJ/mm procedures. The width and depth of grooves were then adjusted to accommodate a comfortable number of beads for each layer and enough depth to reduce base plate dilution effects for the final layer. The finally selected dimensions of the machined grooves were : 25mm wide; 6 and 13mm deep respectively for the low and high input welds.

The peak surface temperature was also measured at reheated CG-HAZ locations for both high and low heat input procedures. This was done by placing a thermocouple within 1mm of the first capping bead fusion line. The peak reheating temperature was measured as the next bead was applied at 50% overlap. The measured value for both heat inputs was approximately 300°C.

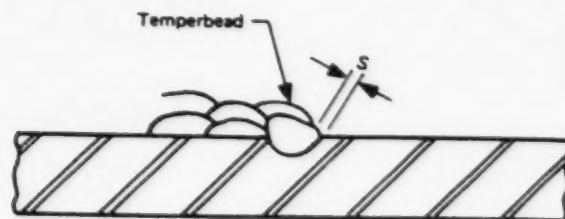
(b) Development of Temperbead Welding Procedures (Sequences #3 and #4)

A review of the literature (6-9) describing accepted temperbead strategies was completed before the development work started in the laboratory. The trials attempted to verify the effectiveness of such techniques. Since the panels being produced were intended for surface weld zone corrosion testing only, the effect of temperbead procedures in this area was of primary concern.

The temperbead techniques described in the literature have the objective of refining the coarse grain heat affected zone of a weld layer deposited on the base metal surface by heating it to a temperature in the vicinity of the upper critical temperature, i.e. by reaustenitizing, such that austenitic grain size does not exceed approximately 50 microns. If these objectives could be met then local weld repairs could be performed without PWHT while restoring weld zone properties. The risk of hydrogen assisted cracking, caustic embrittlement and reheat cracking in the repair area would also be reduced. These aspects provided the impetus for the development of such welding procedures, primarily for repairs in the pressure vessel industry, where post weld heat treatments for large structures may be impractical or expensive. A full description of various procedures is described in the referenced literature.

In applying the above mentioned techniques to welds for seawater corrosion resistance, it should be pointed out that the procedures were developed to enhance the resistance of the entire volume of the coarse grain HAZ of the repair welds since hydrogen cracking, stress corrosion cracking and reheat cracking can occur in the region of susceptible microstructure even if it happens to be subsurface. Consequently, greater attention is paid to the overall extent of refinement along the surface of the cavity. The extent of refinement at the exposed surface, i.e. at the toe of the first or last bead of the final layer has not been given as much attention. For welds to be tested for seawater corrosion resistance, this is precisely the area which will form the basis of assessing HAZ preferential corrosion, and the effectiveness of the temper bead technique.

In such a situation, the heat input and placement of the first bead of the temperbead (second) layer, and unremelted width 's' of the first (or last) bead of the butter (first) layer are of critical importance. (See sketch below.)



Step 3

Such a technique has also been termed as the "three bead" technique, and as alluded to before, there is very little information in the published literature looking at the effect of changes in welding variables on the effectiveness of the technique. Only Ontario Hydro Research Laboratories seem to have recently looked at these aspects in detail (10), and the values of 's' have been variously suggested to be 2mm, and 25% of the bead width in the first layer, depending on heat inputs, etc.

The parameters and preheats suggested by Ontario Hydro are as follows:

<u>Preheat (°C)*</u>	<u>Electrode Diameter/Current</u>		<u>Heat Input Ratio</u>
	<u>1st Butter Layer</u>	<u>2nd Temperbead Layer</u>	
177°C	2.4mm/105A	3.2mm/130A	1:2

*(177C for nuclear components, 232°C for sour service)

It was also suggested that Ontario Hydro procedures were effective at preheat levels as low as 97°C. The above parameters, therefore, formed the basis of "3 bead" development work in this program which used spare CSA G40.21 Gr 350WT material (not program steel). A preheat temperature of 150°C was used for initial trials using high and low heat input procedures with a target temper bead offset of 2mm as recommended. The low heat input butter layer (.5kJ/mm) was applied using 2.4mm E8018-C1 electrodes followed by a temperbead applied at twice the heat input (1.0 kJ/mm), using a 3.2mm electrode. A 4mm and 5mm diameter combination was used for high heat input procedures (1.25 kJ/mm and 2.25 kJ/mm).

(c) Results of Temperbead Procedure Development (Three bead technique)

Microstructural observation and hardness testing of welds produced using the Ontario Hydro procedure (at 150°C) did not show recrystallized toe areas for either low or high heat input procedures. The 2mm offset also proved to be difficult to maintain when applying a weld over the crown of the butter layer. This was particularly true for the high heat input procedure where temper bead volumes were relatively large. The 150°C preheat was considered a preferred preheat temperature since higher values would be more difficult to maintain using hand held oxy-fuel preheating equipment. This preheat level is also well above the 97°C minimum recommended and was, therefore, used in subsequent trials. Using a 150°C preheat, butter layer crowns were therefore dressed to various heights to assist deposition consistency ensuring the target 2mm offset could be maintained.

Sections were removed to evaluate virgin HAZ and reheated HAZ microstructure and hardnesses. The trial matrix and results are illustrated in Table IV. Micrographs of all trial welds are referenced in this table and are presented in Figures 3 to 8.

Recrystallized HAZ's were observed only when the butter layer was ground flush with the plate surface using a 150°preheat. Since grinding these beads flush was difficult and often resulted in over grinding, the use of moderate grinding (leaving approximately 0.8mm of butter layer) and a higher 200°C preheat was tried. This proved effective as the toe area HAZ hardness was reduced from 322 Hv₁₀ to approximately 200 Hv₁₀ for low heat input procedures, same as for the flush ground low heat input procedures.

The higher heat input procedure also showed significant softening where the original hardness of 267 Hv₁₀ was reduced to about 185 Hv₁₀ after temperbead application. Micro-structure observation showed complete recrystallization in the toe areas. These results therefore formed the basis of temperbead procedures applied to program panels where preheats were maintained between 200-225°C using a 2mm offset distance with butter layers ground to approximately 0.8mm in height before applying temperbead layers.

It should be noted that the 2mm offset between the toe HAZ and the temperbead edge can only be considered as a nominal value. The actual distance, due to the nature of the SMAW process varied between about 1 and 3mm. This could result in a variety of results along a panel length during subsequent corrosion testing. Limited panel production was also done with a target offset of 1mm for comparison against the standard 2mm offset.

The required precision in bead placement to reliably achieve significant HAZ softening, as demonstrated during these trials, suggest that such procedures would be difficult to apply in field application. CEGB investigators also suggest that proper procedure application in this toe area is unreliable since, for critical applications, grinding of the surface 2mm below the original plate surface, after complete temperbead weld repair, is recommended. This grinding would increase the likelihood of refined HAZ being exposed at the surface.

The objective of producing these panels, however, was to assess the performance of recrystallized HAZ toe regions exposed to seawater and not necessarily the suitability of procedures for field application. If a significant improvement in seawater corrosion resistance is observed, alternative methods of HAZ refinement could be developed. Such alternatives could include P-GTAW remelting where autogenous remelting of butter beads at slow travel speeds may be a practical option although some degree of operator skill would be expected.

3.3 Fabrication of Pulsed Gas Metal Arc Weldments (P-GMAW)

Twenty-four P-GMAW panels were produced following development of procedures using machined 20mm deep grooves with 60° included angle and a nominal heat input of 2.0 kJ/mm. Procedure development for this portion was again straight forward where comfortable parameters (amps, volts, travel speed) were established to repeatably fit in the groove with a 3 pass capping layer. The final capping layer was deposited in a left to right deposition sequence using a target 50% bead overlap.

All P-GMAW weldments were fabricated in the flat position using a fully automatic arrangement. Panels were restrained to avoid excessive distortion. The welding arrangement used is illustrated in Figure 9 with a procedure development weld in place.

Since it was anticipated that a difference in corrosion susceptibilities would be realized for each side of the final layer (based on previous corrosion studies), the peak reheating temperature was measured in the HAZ region of the first capping bead as in SMAW welds. The thermocouple measurement location was within 1mm of the fusion line. The peak temperature measured was approximately 300°C. This was similar to the peak temperature measured for SMAW welds for both high and low heat input procedures.

The amperage and voltage fluctuated for different wires and gases causing calculated heat input to vary between 1.8 and 2.2 kJ/mm. Bead volumes were, however, held constant by maintaining constant wire feed speeds. This difference in amperage and voltage was probably due to changes in electrical properties for different wires and gases since all other settings, including electrical stick out, were maintained the same throughout.

A full description of the P-GMAW test matrix is shown in Table V. In addition to the twenty four plates required for the program (two steels, two shielding gases, six wires), two panels, approximately 375mm long were welded after normalizing the 1.63% Mn OLAC steel in order that the effect of the base plate microstructure on the weld zone corrosion could be assessed when the corrosion tests are carried out.

The welding procedure used for panel production is summarized in Appendix B, and is followed by a representative weld cross section.

4.0 HAZ MICROSTRUCTURES AND HARDNESS VALUES

4.1 SMAW Panels

Cross sections were removed from the welded low manganese steel panels for representative HAZ microstructural analyses and hardness testing. The hardness readings for each sequence and heat input are presented in Table VI. HAZ microstructures are illustrated in Figures 10-15 and referenced in Table VI.

Toe area HAZ hardness measurements for the low heat input sequence #2 procedures indicate no reduction in hardness for the reheated (50% overlap) HAZ. Both the reheated and as-deposited HAZ hardness were in the 360-365 Hv₁₀ range. Observation of HAZ microstructures in the optical microscope from this procedure also did not reveal any discernible changes.

Similar results were seen for the higher heat input sequence #2 procedure, however, as expected, the hardness levels were lower due to slower cooling rates. The HAZ hardness was in the 260 Hv₁₀ range for both the as deposited and the reheated weld toes. Representative HAZ micrographs for sequence #2 weldments are presented in Figures 10 & 11. These results are supported by HAZ temperature measurements done during procedure development where peak temperatures were in the 300°C range.

In general, the temperbead procedures were effective in recrystallizing the HAZ (Figure 12-15), the resulting HAZ hardnesses being much lower - in the range 200 to 250 Hv₁₀. Suprisingly though, the 1mm offset procedure yielded higher HAZ hardness value than did the 2mm offset procedure. Although the corresponding photomicrographs are included in figures 12 to 15, a more careful microstructural examination would be needed on corrosion test specimens to relate the offset and HAZ hardness to the corrosion resistance.

4.2 P-GMAW Panels

The hardness measurements for the representative P-GMAW weld (I.D. 2PAC5) are included in Table VI. The as deposited and reheated toe area HAZ microstructures are illustrated in Figure 16. Again HAZ morphologies are similar with no visible evidence of reheating effects. CG-HAZ hardness measurements suggest some softening occurred where the as deposited hardness of 317 Hv₁₀ was reduced to 275 Hv₁₀. This was not supported by cooling rate measurements where a peak HAZ reheating temperature of 300°C was recorded. This could possibly be due to the placement of the thermocouple, some distance (>1mm) away from the fusion boundary.

5.0 SUMMARY

A total of fifty four weld panels made by the shielded metal arc and the pulsed gas metal arc processes have been supplied to Metals Technology Laboratories for further evaluation in regard to their seawater corrosion resistance.

For the shielded metal arc weldments, the corrosion testing should help to establish if recrystallization of the HAZ or the reheating of the HAZ to subcritical temperature lead to significant improvement in HAZ corrosion resistance. This effect can be established for two levels of Mn in the base steel, at two heat input levels and for weld metals that themselves could be more (E7018-1) or less (E8018C-1, E7018-RCR) susceptible to sea water corrosion.

The pulsed gas metal arc welding will aid in studying the effect of weld metal chemistry including oxygen content and base plate microstructure (OLAC vs normalized) on weld zone corrosion.

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TABLES AND FIGURES

TABLE I: CHEMICAL ANALYSIS (WT %) OF THE BASE MATERIAL STEELS

Steel Designator	Thickness (mm)	C	Mn	S	P	Si	Cr	Ni	Cu	Al	Nb	V
1	35	.10	1.62	.003	.011	.22	.03	.62	.25	.02	.01	.04
2	25	.18	1.23	.010	.012	.23	.01	.01	.01	.033	<.01	.047

TABLE II: TYPICAL CHEMICAL ANALYSIS (WT %) FOR GMAW WIRES USED IN THE PROGRAM

Wire	Class	C	Mn	P	S	Si	Cu	Ni	Ti	Cr	B
C-Mn-Si	ER70S-6 (LTec-86)	.1	1.6	.012	.016	.93	.04				
C-Mn-Si	ER70S-3 (LTec-82)	.1	1.05	.012	.016	.5	.05				
C-Mn-Ti-B	Kobe MG50LT	.07	1.9	.013	.012	.40	.18	.02	.045	.11	.004
C-Mn-Si-Ti	ER70S-6 Thyssen KNova	.06	1.6	.013	.005	.85	.10		.04		
C-Mn-1.3Ni	ER80S-6 Thyssen K-5Ni	.10	1.37	.006	.007	.68		1.35			
C-Mn-2.5Ni	ER80S-Ni2 Thyssen Ni2.5	.08	1.25	.008	.007	.40		2.43			

APPENDIX B

P-GMAW PROCEDURE AND MACROSECTION

TABLE III: IDENTIFICATION SCHEME FOR SHIELDED METAL ARC WELDMENTS (SMAW)

WELD I.D.	STEEL[1]	PROCESS[2]	ELECTRODE	HEAT INPUT (kJ/mm)		ELECTRODE DIA. (mm)
1SJ1	1	S	LA7018	1	Seq. 1	3.2
1SJ2	1	S	LA7018	2.5	Seq. 1	5.0
1SK1	1	S	LA18 Plus	1	Seq. 1	3.2
1SK2	1	S	LA18 Plus	2.5	Seq. 1	5.0
1SL1	1	S	AA8018C1	1	Seq. 1	3.2
1SL2	1	S	AA8018C1	2.5	Seq. 1	5.0
1SM1	1	S	RCR	1	Seq. 1	3.2
1SM2	1	S	RCR	2.5	Seq. 1	4.0[3]
1SN1	1	S	AA8018C1	1	Seq. 2	3.2
1SN2	1	S	AA8018C1	2.5	Seq. 2	5.0
1SP1	1	S	AA8018C1	1	Seq. 3	2.4, 3.2 (2mm offset)
1SP2	1	S	AA8018C1	2.5	Seq. 3	4.0, 5.0 (2mm offset)
1SQ1*	1	S	AA8018C1	1	Seq. 4	2.4, 3.2 (1mm offset)
1SQ2*	1	S	AA8018C1	2.5	Seq. 4	4.0, 5.0 (1mm offset)
2SJ1	2	S	LA7018	1	Seq. 1	3.2
2SJ2	2	S	LA7018	2.5	Seq. 1	5.0
2SK1	2	S	LA18 Plus	1	Seq. 1	3.2
2SK2	2	S	LA18 Plus	2.5	Seq. 1	5.0
2SL1	2	S	AA8018C1	1	Seq. 1	3.2
2SL2	2	S	AA8018C1	2.5	Seq. 1	5.0
2SM1	2	S	RCR	1	Seq. 1	3.2
2SM2	2	S	RCR	2.5	Seq. 1	4.0
2SN1	2	S	AA8018C1	1	Seq. 2	3.2
2SN2	2	S	AA8018C1	2.5	Seq. 2	5.0
2SP1	2	S	AA8018C1	1	Seq. 3	2.4, 3.2 (2mm offset)
2SP2	2	S	AA8018C1	2.5	Seq. 3	4.0, 5.0 (2mm offset)
2SQ1*	2	S	AA8018C1	1	Seq. 4	2.4, 3.2 (1mm offset)
2SQ2*	2	S	AA8018C1	2.5	Seq. 4	4.0, 5.0 (1mm offset)

* These panels were ~ 375mm long.

[1] Steel 1 = 1.62% Mn, Steel 2 = 1.23% Mn

[2] S = Shield Metal Arc Welding

[3] 5.0 mm RCR was not available

TABLE IV : Results of 3 Bead Temperbead Trials

Series	Sample ID	Heat Input	Preheat(°C)	Butter Layer Height (mm)	Deposit Conditions [2]	HAZ Condition [3]	Avg. HAZ Hardness (Hv ₁₀)	Micrograph (Fig #)
I	LA-2	5 kJ/mm	150	UT	B TB	AD NR	328 307	Fig 3
	LA-3	5 & 1.0 kJ/mm	150					
II	LC	5 kJ/mm	150	1.6 0.8	B TB TB	AD NR NR	319 277 277	Fig 4
	LC-1	5 & 1.0 kJ/mm	150					
	LC-2	5 & 1.0 kJ/mm	150					
III	LD	5 kJ/mm	20	flush 0.8	B TB TB	AD R R	322 205 197	Fig 5
	LD-1	5 & 1.0 kJ/mm	150					
	LD-2	5 & 1.0 kJ/mm	200					
IV	HA-2	1.25 kJ/mm	150	UT	B TB	AD NR	290 284	Fig 6
	HA-3	1.25 & 2.5 kJ/mm	150					
V	HC	1.25 kJ/mm	150	1.6 0.8	B TB TB	AD NR NR	311 268 262	Fig 7
	HC-1	1.25 & 2.5 kJ/mm	150					
	HC-2	1.25 & 2.5 kJ/mm	150					
VI	HD	1.25 kJ/mm	20	UT flush 0.8	B TB TB	AD R R	267 184 182	Fig 8
	HD-1	1.23 & 2.5 kJ/mm	150					
	HD-2	1.23 & 2.5 kJ/mm	200					
UT: Untouched		B: Butter Layer		TB: Temperbead				
AD: As Deposited		R: Refined		NR: Not Refined				

TABLE V: IDENTIFICATION SCHEME FOR PULSED - GAS METAL ARC WELDMENTS (P-GMAW)

<u>WELD I.D.</u>	<u>STEEL[1]</u>	<u>PROCESS[2]</u>	<u>WIRE[3]</u>	<u>GAS[4]</u>
1PAC5	1	P	A	C5
1PAC20	1	P	A	C20
1PBC5	1	P	B	C5
1PBC20	1	P	B	C20
1PCC5	1	P	C	C5
1PCC20	1	P	C	C20
1PDC5	1	P	D	C5
1PDC20	1	P	D	C20
1PEC5	1	P	E	C5
1PEC20	1	P	E	C20
1PFC5	1	P	F	C5
1PFC20	1	P	F	C20
1PGC5*	1	P	F	C5 (as 1PFC5 on normalized plate)
1PGC20*	1	P	F	C20 (as 1PFC5 on normalized plate)
2PAC5	2	P	A	C5
2PAC20	2	P	A	C20
2PBC5	2	P	B	C5
2PBC20	2	P	B	C20
2PCC5	2	P	C	C5
2PCC20	2	P	C	C20
2PDC5	2	P	D	C5
2PDC20	2	P	D	C20
2PEC5	2	P	E	C5
2PEC20	2	P	E	C20
2PFC5	2	P	F	C5
2PFC20	2	P	F	C20

[1] Steel 1 = 1.62% Mn, Steel 2 = 1.23% Mn

[2] P = Pulsed - Gas Metal Arc Welding; Heat input 1.8 - 2.2 for all welds at constant wire feed and travel speeds.

[3] Wire Designations:

A	L-Tec 86	ER70S-6
B	L-Tec 82	ER70S-3
C	Kobe MG50LT	C-Mn-Ti-B
D	K-Nova (ER70S-6)	C-Mn-Si-Ti
E	K-5Ni (ER80S-6)	C-Mn-1.3Ni
F	Ni 2.5 (ER80S-Ni2)	C-Mn-2.5Ni

[4] Shielding Gases

C5 = Ar - 95%; CO₂ - 5%

C20 = Ar - 80%; CO₂ - 20%

* These panels were 375mm long.

Table VI
Hardness Test Results from Supplied Panel Weldments (steel #2 only - low Mn)

Panel I.D.	Weld Bead Sequence No.*	Heat Input (kJ/mm)	CG-HAZ Hardness Hv ₁₀ as deposited(Fig #) reheated(Fig #)		Notes
2SN1	2	1.0	LS=360	RS=365 10	Left side only reheated with no hardness change. Notice lower readings for higher heat input. Note softening from 2SN1 and 2SN2 as deposited values.
2SN2	2	2.5	LS=262	RS=260 11	
2SP1	3(TB)	1.0		LS=225 12a RS=222 12b	
2SP2	3(TB)	2.5		LS=215 13a RS=213 13b	
2SQ1	4(TB)	1.0		LS=246 14a RS=254 14b	
2SQ2	4(TB)	2.5		LS=231 15a RS=216 15b	
2PAC5	P-GMAW	2.5	LS=317	RS=275	

TB - Temperbead Procedure

RS - Right Side

LS - Left Side

* Sequence number 1 results are not presented here since hardness levels are represented by left side sequence #2.

Relative corrosion rate of NWH-bar heat-affected-zones

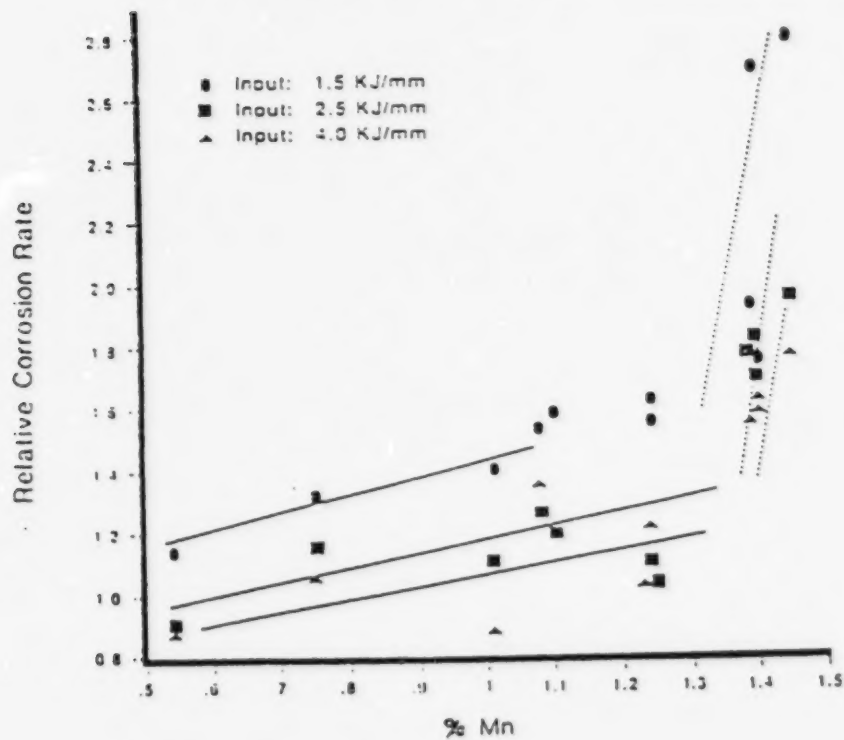
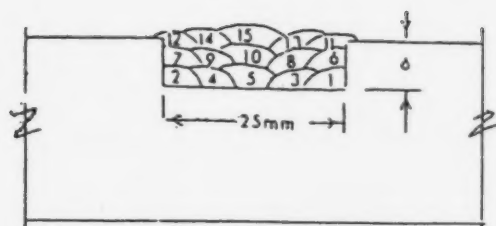
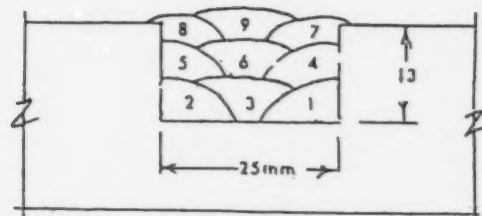


Figure 1: Relative rates of heat affected zone corrosion of NWH bars at various heat inputs as a function of Mn content. (Based on Reference 2)

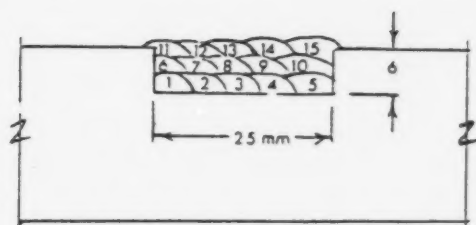


low heat input

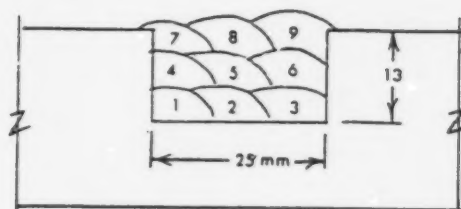


high heat input

a) Sequence #1

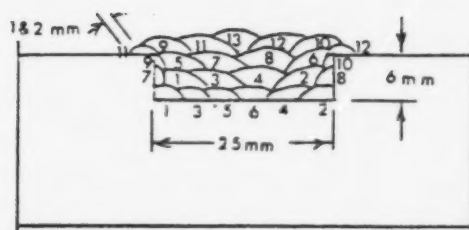


low heat input

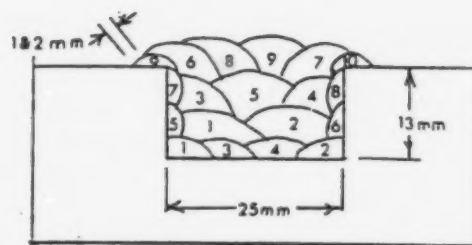


high heat input

b) Sequence #2



low heat input



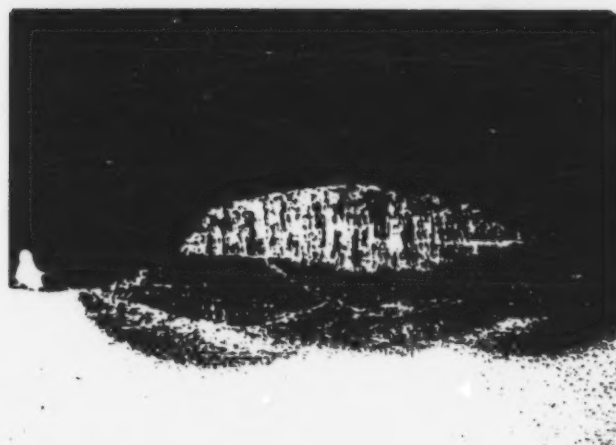
high heat input

c) Sequences #3 and 4

Figure 2
Weld Metal Deposition Sequences



a) 0.5 kJ/mm butter layer
CG-HAZ = 328 Hv

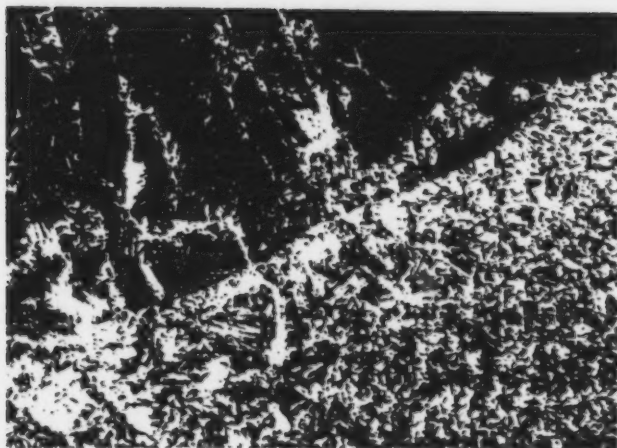


b) 1.0 kJ/mm Temperbead
area measured offset = 2.4 mm

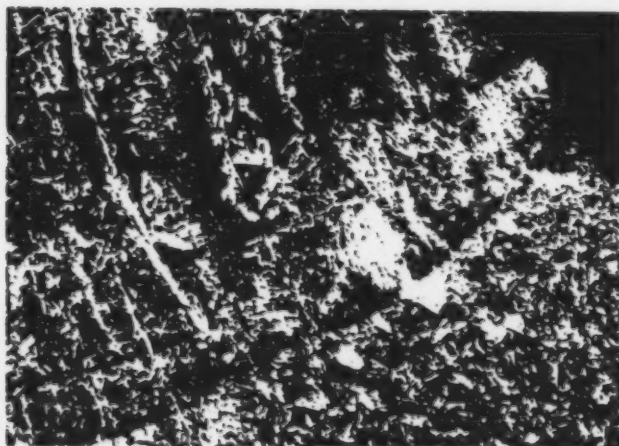


c) Unrefined Toe HAZ
CG-HAZ = 307 Hv

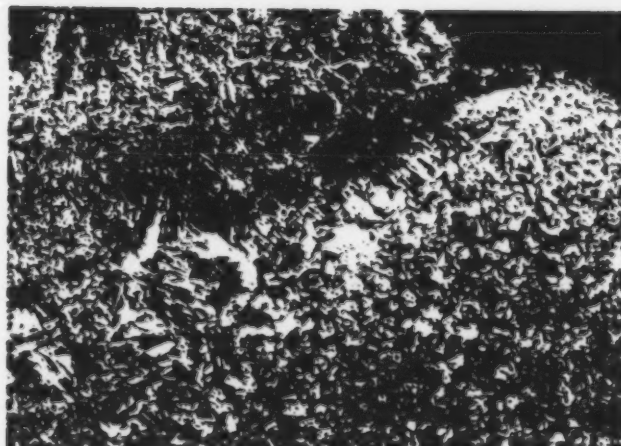
Figure 3
Ontario Hydro Procedure, Low Heat Input (Series I)



a) As deposited toe area
for butter layer.
CG-HAZ = 319 Hv

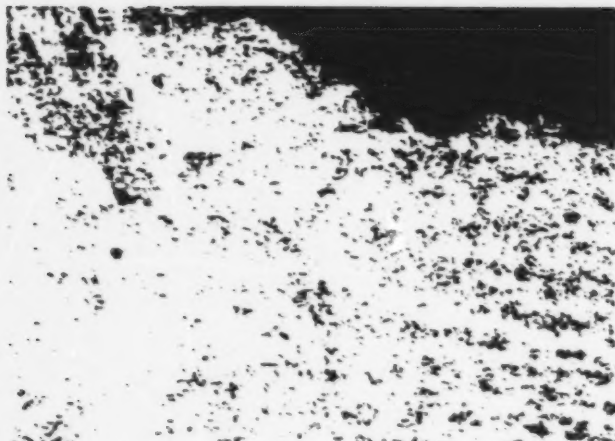


b) Ground butter layer = 1.6mm
CG-HAZ = 277 Hv (softened)
Area measured offset = 2.4mm

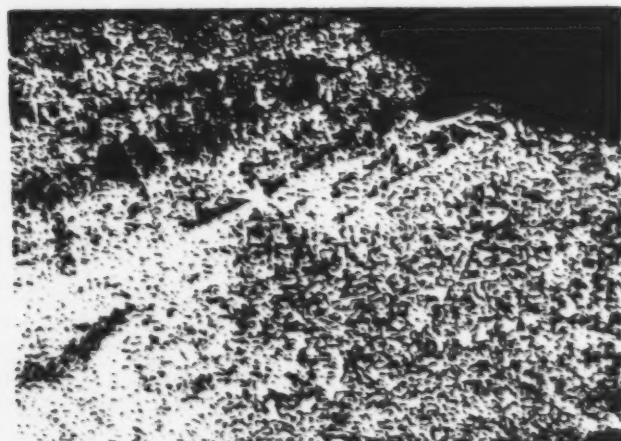


c) Ground butter layer = 0.8mm
CG-HAZ = 277 Hv (softened)
Area measured offset = 2.0mm

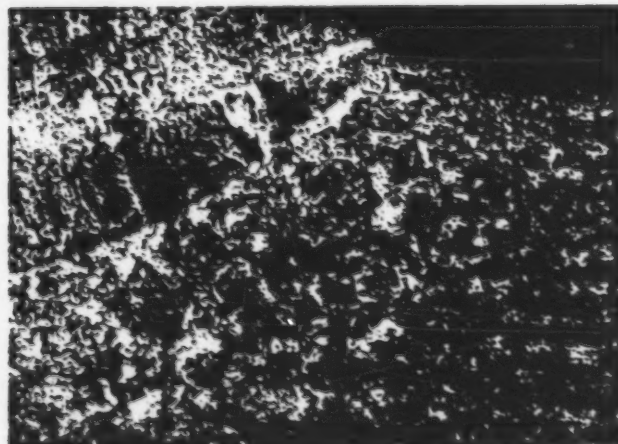
Figure 4
Low Heat Input, Ground Layers (Series II)



a) As deposited toe area
for butter layer.
CG-HAZ = 322 Hv₁₀

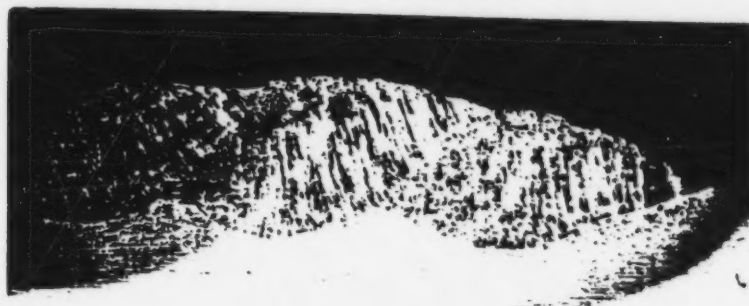


b) Flush ground reheated
CG-HAZ = 205 Hv₁₀ (refined)
measured offset = 1.8mm
Preheat = 150°C

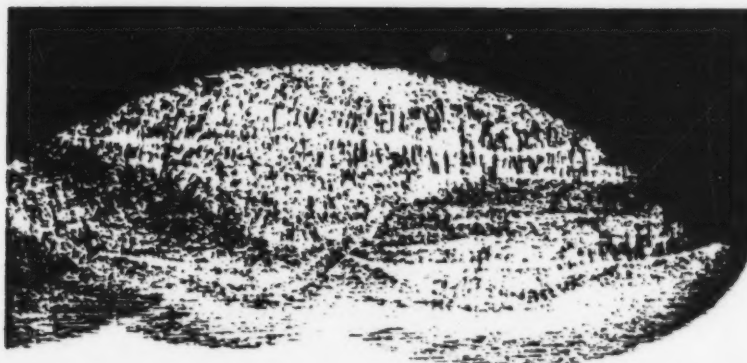


c) .8mm ground butter layer
CG-HAZ = 197 Hv₁₀ (refined)
measured offset = 2.2mm
Preheat = 200°C

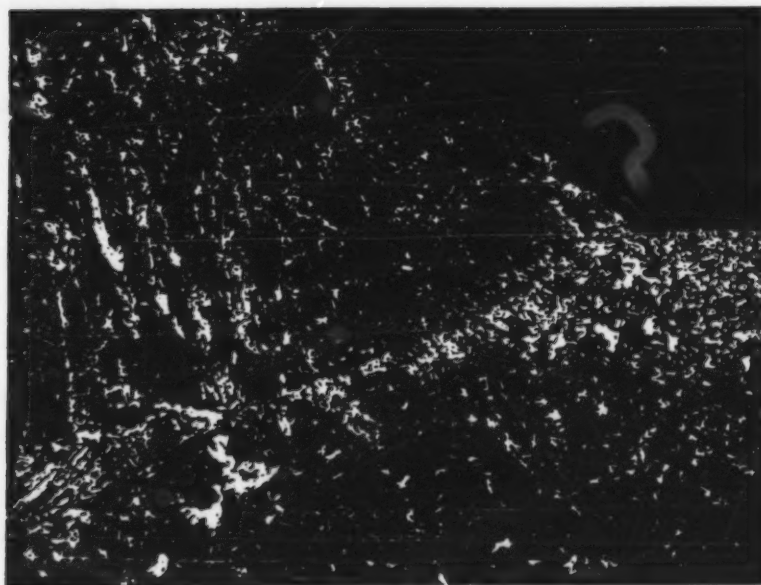
Figure 5
Low Heat Input, Flush Ground Layer and Increased Preheat (Series III)



a) 1.25 kJ/mm butter layer
CG-HAZ = 290 Hv₁₀

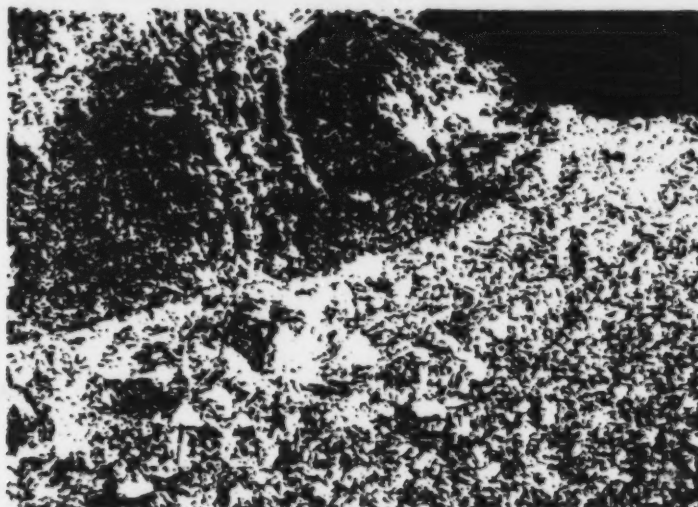


b) 2.5 kJ/mm Temperbead
Measured offset = 2.6mm

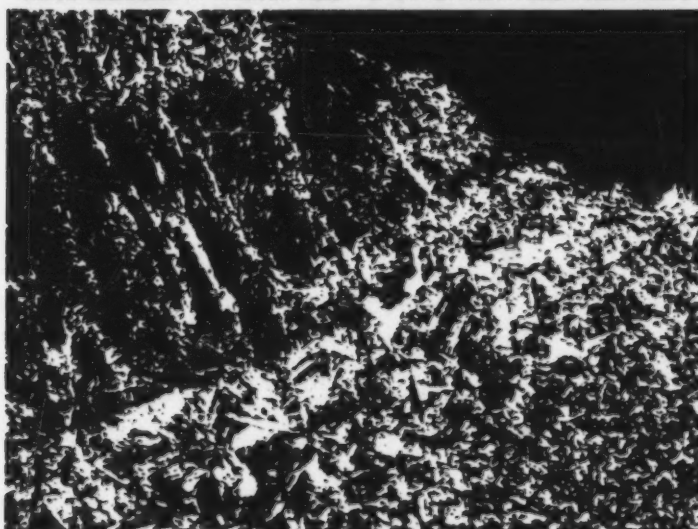


c) Unrefined Toe HAZ.
CG-HAZ = 284 Hv₁₀

Figure 6
Ontaro Hydro Procedure, High Heat Input (Series IV)



a) As deposited toe area
for butter layer.
CG-HAZ = 311 Hv₁₀

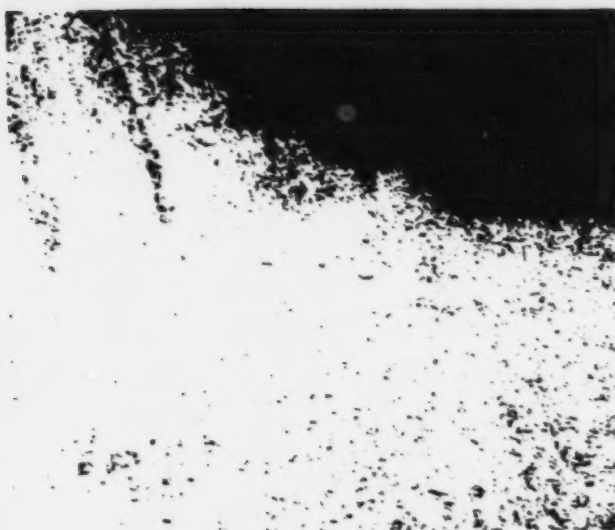


b) Ground butter layer = 1.6mm
CG-HAZ = 268 Hv₁₀ (softened)
Measured offset = 2.4mm

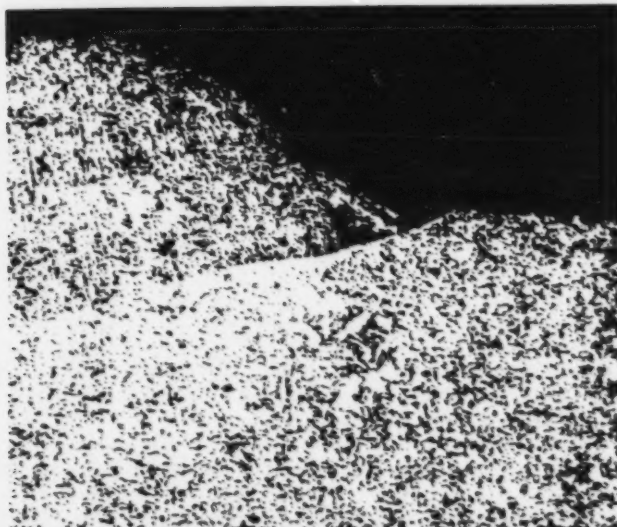


c) Ground butter layer = 0.8mm
CG-HAZ = 262 Hv₁₀ (softened)
Measured offset = 2.6mm

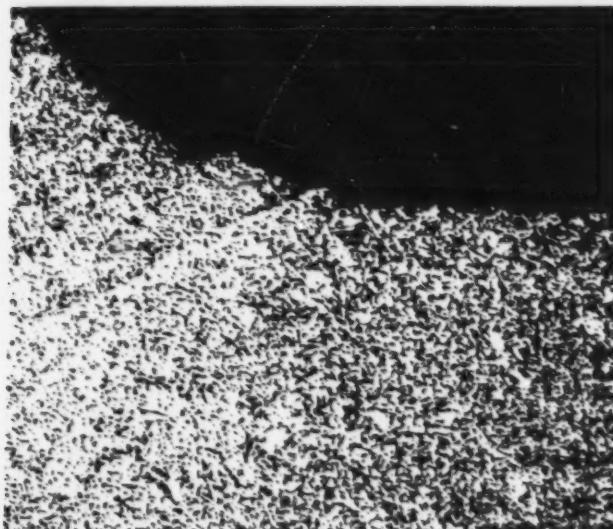
Figure 7
High Heat Input, Ground Layers (Series V)



a) As deposited toe area
for butter layer.
CG-HAZ = 267 Hv₁₀



b) Flush ground reheated
CG-HAZ = 184 Hv₁₀ (refined)
measured offset = 2mm
Preheat = 150°C

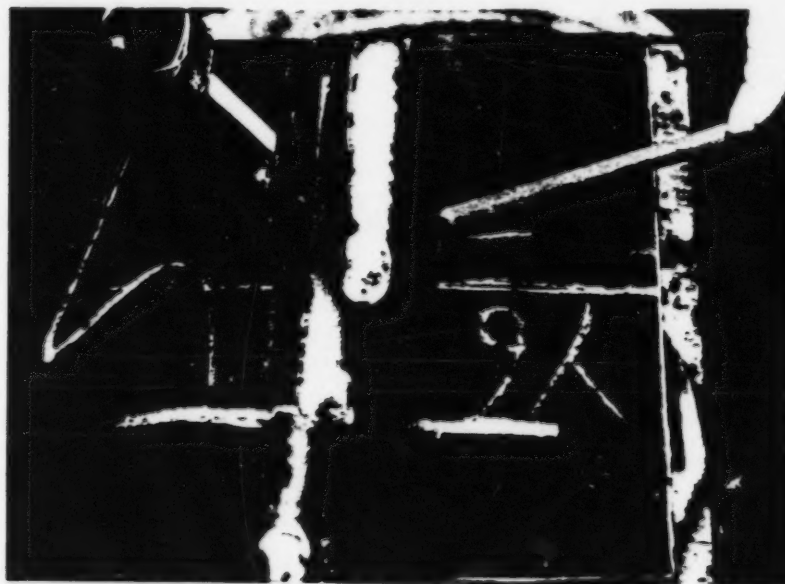


c) .8mm ground butter layer
CG-HAZ = 182 Hv₁₀ (refined)
measured offset = 2mm
Preheat = 200°C

Figure 8
High Heat Input, Flush Ground Butter and Increased Preheat (Series VI)

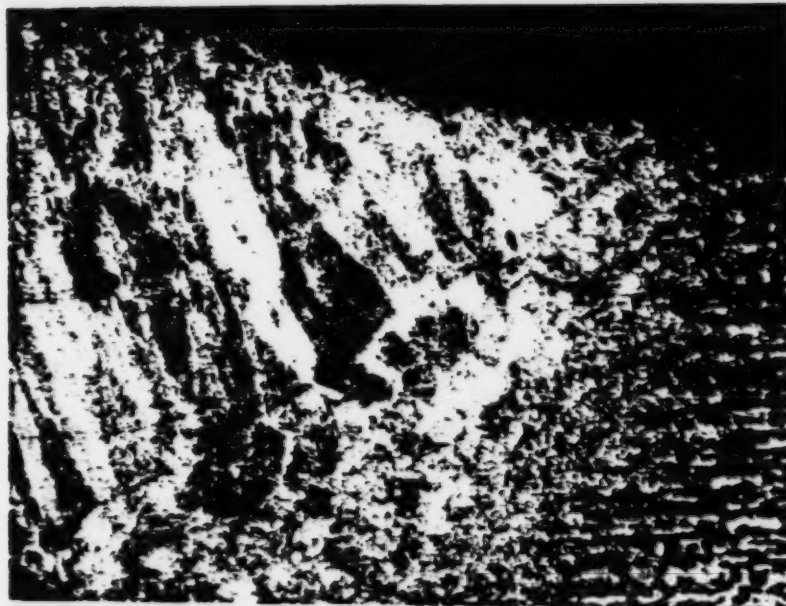


a) Measuring toe area cooling rates for 50% overlap P-GMAW procedure.
(restraint jig also shown)



b) Weld bead placement for 2.0kJ/mm P-GMAW procedure.
(Thermocouple location also shown)

Figure 9
P-GMAW Welding Station and Procedure Development Illustrations



a) Low Heat Input Sequence #2. Left Side CG-HAZ = 360 Hv₁₀ (neg# 12020) x 50

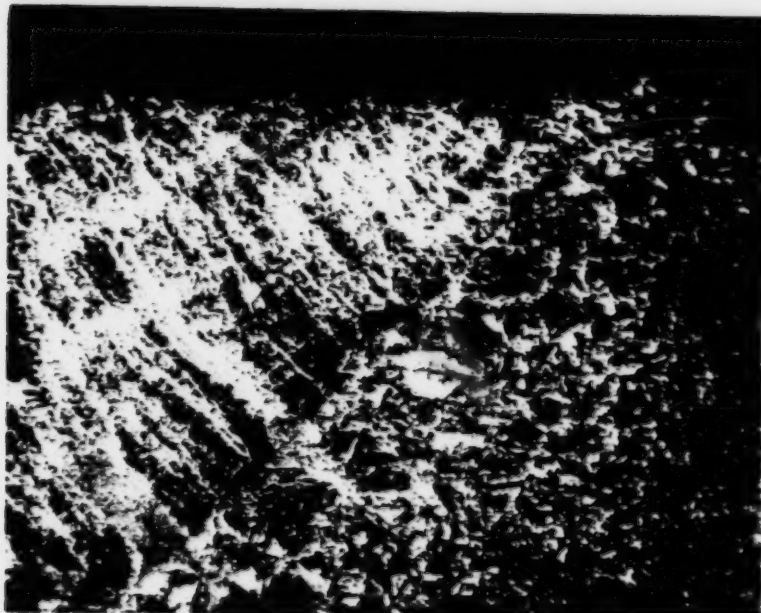


b) Low Heat Input Sequence #2. Right Side CG-HAZ = 365 Hv₁₀ (neg. #12019) x 50

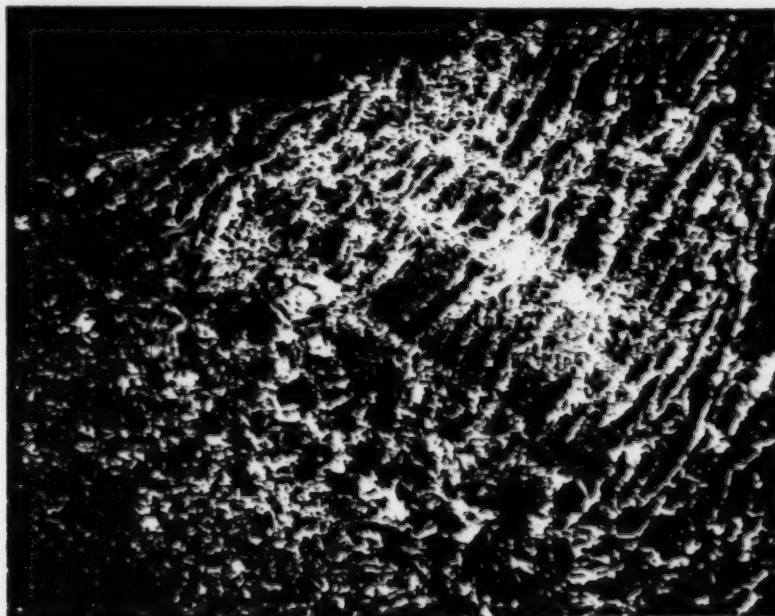
Figure 10

Low Heat Input Sequence #2. (Panel 2SN1)

No visible HAZ refinement or reduction in measured hardness for 50% bead overlap.



a) High Heat Input Sequence #2. Left Side CG-HAZ = 262 Hv₁₀ (neg# 12022),x 50



b) High Heat Input Sequence #2. Right Side CG-HAZ = 260 Hv₁₀ (neg #12021),x 50

Figure 11

High Heat Input Sequence #2. (Panel 2SN2)

No visible HAZ refinement or reduction in measured hardness for 50% bead overlap.

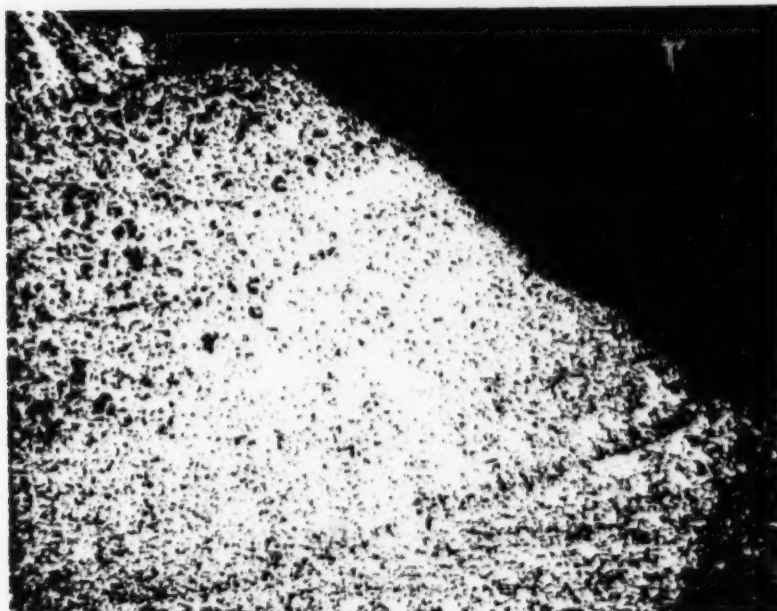


a) Toe area HAZ = 225 Hv₁₀ (measured offset = 2.3mm) Left side, neg# 12116,x 50

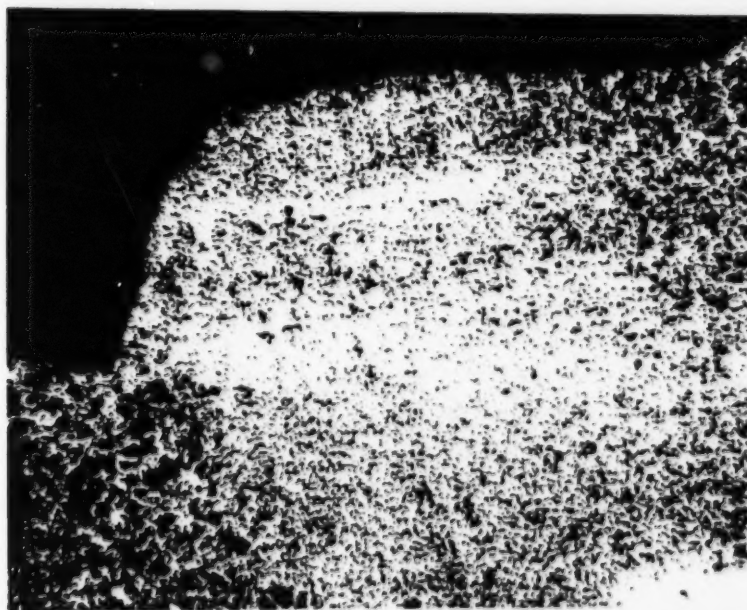


b) Toe area HAZ = 222 Hv₁₀ (measured offset = 2.3mm) Right side, neg# 12112,x 100

Figure 12 (Panel 2SP1)
Sequence #3. Low Heat Input Temperbead Procedure (target offset = 2mm)



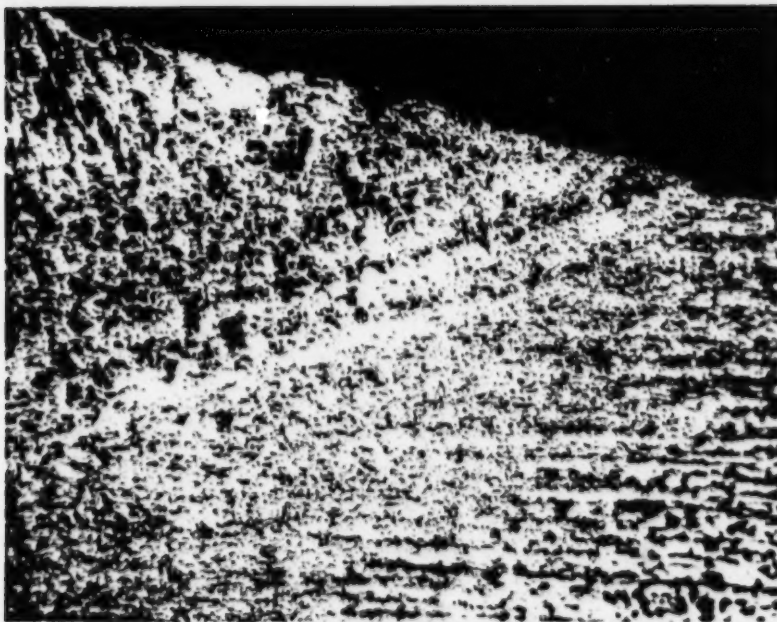
a) Toe area HAZ = 215 Hv₁₀ (measured offset = 1.9mm) Left side, neg# 12018,x 50



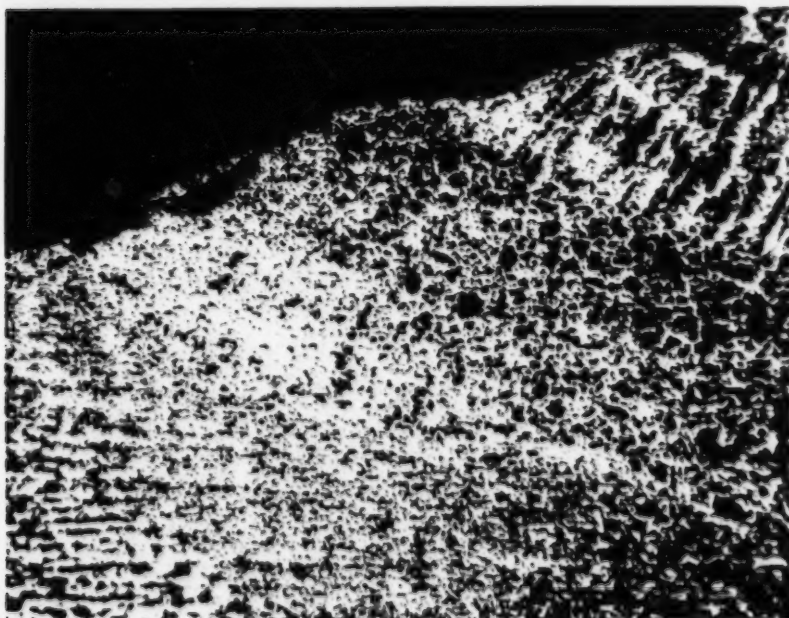
b) Toe area HAZ = 213 Hv₁₀ (measured offset = 2.0 mm) Right side, neg# 12119,x 50

Figure 13 (Panel 2SP2)

Sequence #3. High Heat Input Temperbead Procedure (target offset = 2mm)

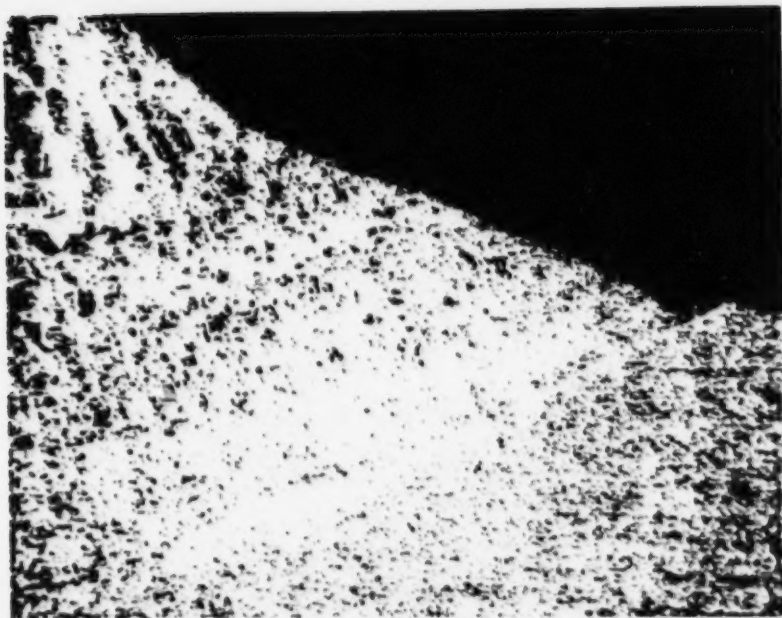


a) Toe area HAZ = 246 Hv₁₀ (measured offset = 1.2mm) Left side, neg# 12012, x 50

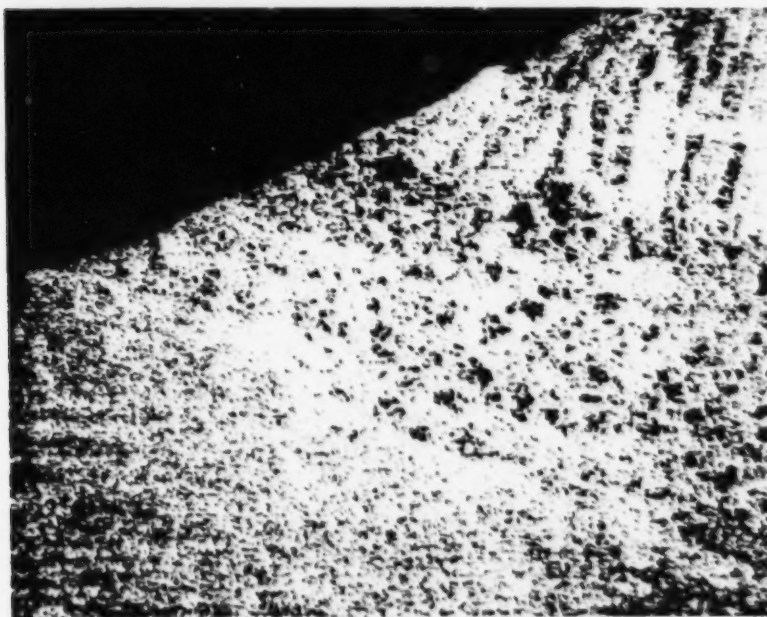


b) Toe area HAZ = 254 Hv₁₀ (measured offset = 1.2mm) Right side, neg# 12011, x 50

Figure 14 (Panel 2SQ2)
Sequence #4. Low Heat Input Temperbead Procedure (target offset = 1mm)

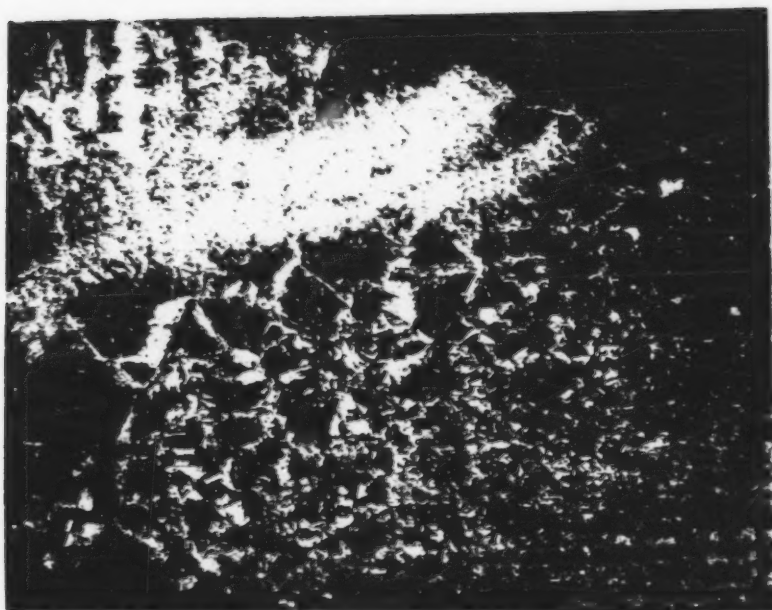


a) Toe area HAZ = 231 Hv₁₀ (measured offset = 1.3mm) Left side, neg# 12014,x 50

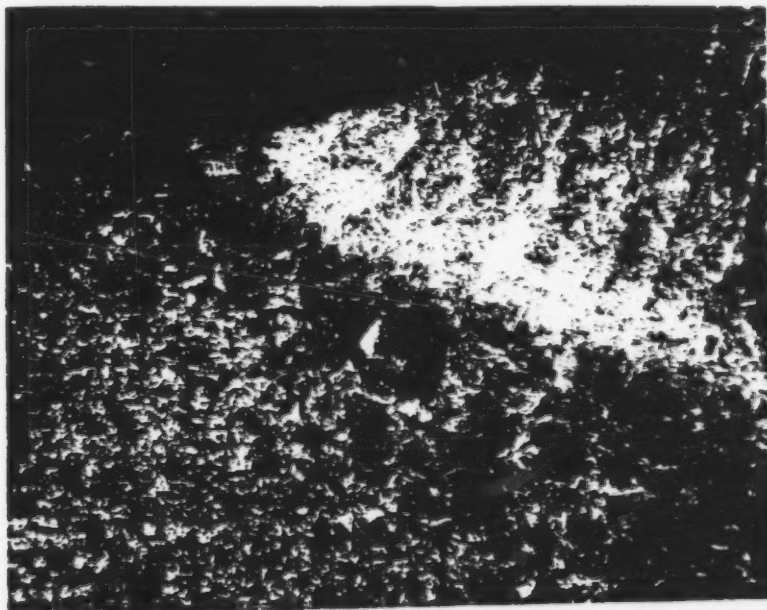


b) Toe area HAZ = 216 Hv₁₀ (measured offset = 1.0mm) Right side, neg# 12013,x 50

Figure 15 (Panel 2SQ2)
Sequence #4. High Heat Input Temperbead Procedure (target offset = 1mm)



a) As Deposited Toe Area (317 Hv₁₀) Left side, neg# 12024,x 50



b) Reheated Toe Area (50% overlap; 275 Hv₁₀) Right side,neg# 12025,x 50

Figure 16 (Panel 2SQ2)
Representative P-GMAW Toe Area Microstructures

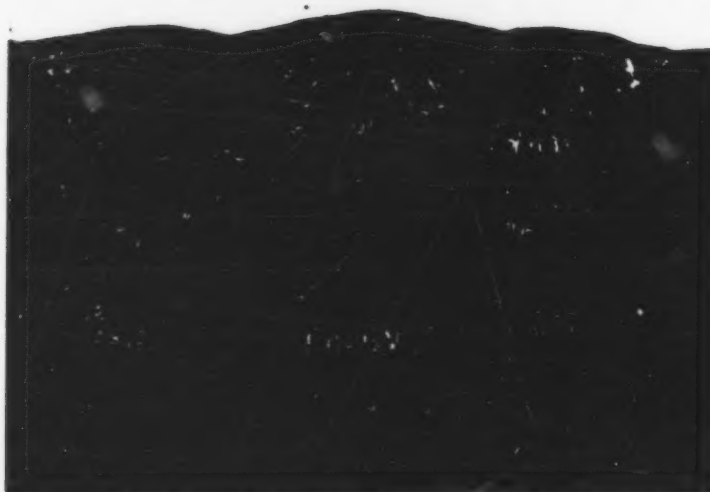
APPENDIX A

SMAW PROCEDURES AND PHOTOMACROGRAPHS

Procedure By:
Lorne Thompson

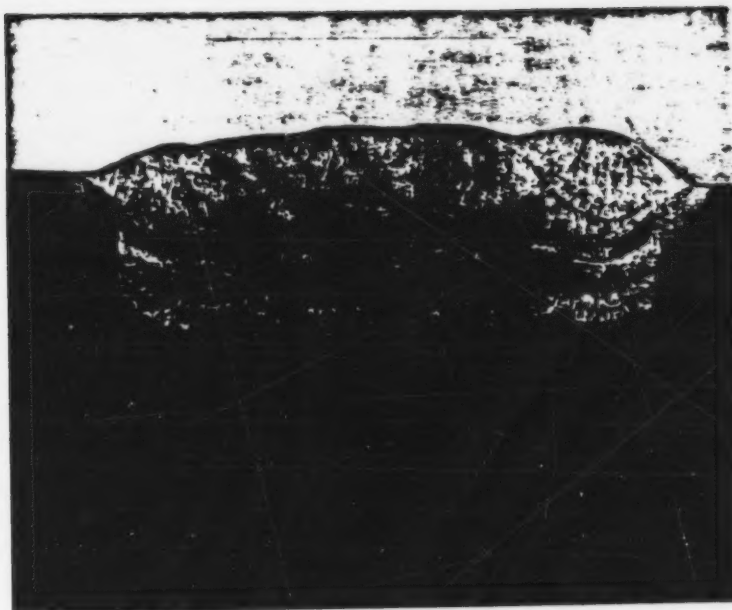


Sequence #1: Low Heat Input Procedure (Panel I.D. 2SL1)
(Neg #12032) x 3

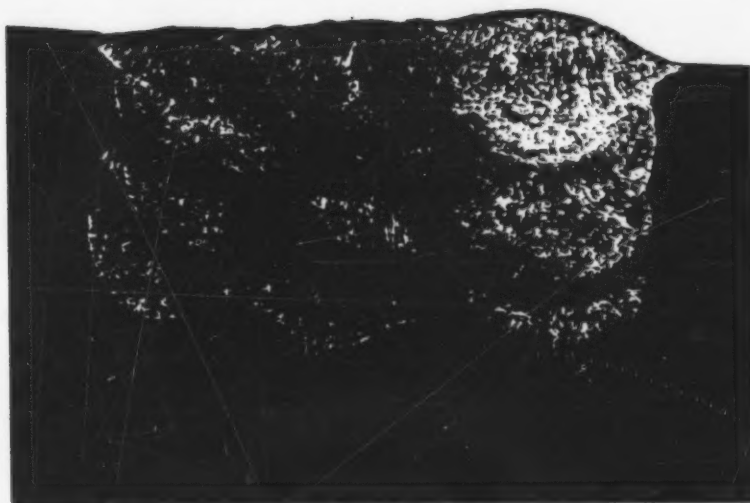


Sequence #1: High Heat Input Procedure (Panel I.D. 2SL2)
(Neg# 12031) x 3

Procedure By:
Lorne Thompson



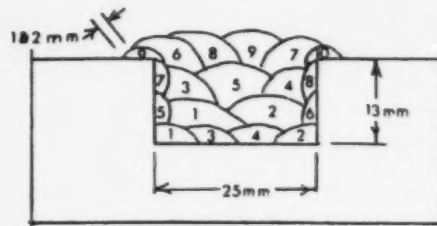
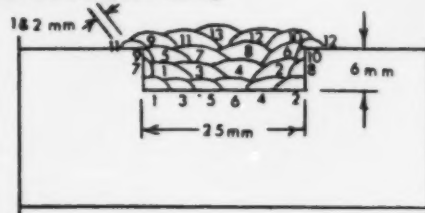
Sequence #2: Low Heat Input Procedure (Panel I.D. 2SN1)
(Neg #12026) x 3



Sequence #2: High Heat Input Procedure (Panel I.D. 2SN2)
(Neg# 12030) x 3

Material Specification: EH36 and EH36 Modified
Welding Process: Shielded Metal Arc Welding
Manual or Machine: Travel speed controlled by
Position of Welding: 1G (Flat position) machine
Filler Metal Brand Name: CLA Dia. = * mm
Filler Metal Classification: E55018-C1
Shielding Gas: --- Flow Rate: ---
Nozzle Orifice Size: ---
Single or Multipass: Multipass
Single or Multiple Arc: Single
Heat Input Requirement (E): 1 kJ/mm & 2.5 kJ/mm
Preheat Temperature: 100°C (200-230°C for temper-
beads)
Interpass Temperature: 100°C
Preheat Method: Oxy-fuel torch
Preparation: All grooves prepared by machining

(Indicate material thickness on drawing)



Joint Preparation

Weld Size	Side	Layer	Pass No.	Amps		WFS		Volts		Travel Speed (i)		E.S.O.						
				I	Dial	mm/min	Dial	V	Dial	mm/min	Dial							
0.5 k.l/mm		butter		90			22			235								
1.0 k.l/mm		fill		135			23			185								
1.25 k.l/mm		butter		170			24			195								
2.5 k.l/mm		fill		240			25			145								

Procedure Notes:

- ① *Electrode diameters for low heat input
② procedure = 2.4mm (butter); 3.2mm (fills)
③ _____
④ *Electrode diameters for high heat input
⑤ procedure = 4.0mm (butter); 5.0mm(fills)
⑥ _____
⑦ _____

Procedure Application Notes:

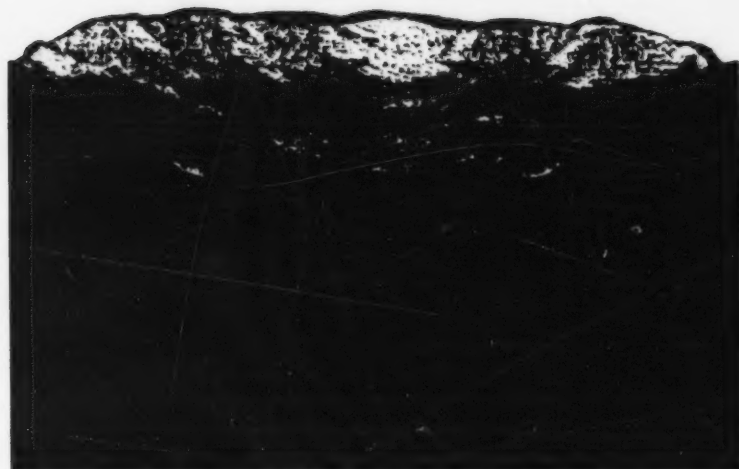
- ① **Sequence No. 4 is essentially the same
② as No. 3 where only the toe temperbead
③ offset was applied at a nominal distance
④ of 1mm instead of 2mm
⑤ _____
⑥ _____
⑦ _____

Date: March 1990

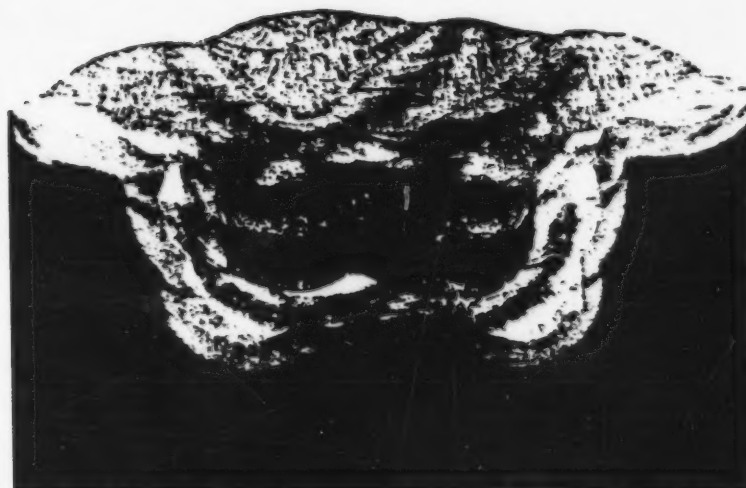
Welder's Name:
Lorne Thompson

Inspected By:
K.G. Morrison

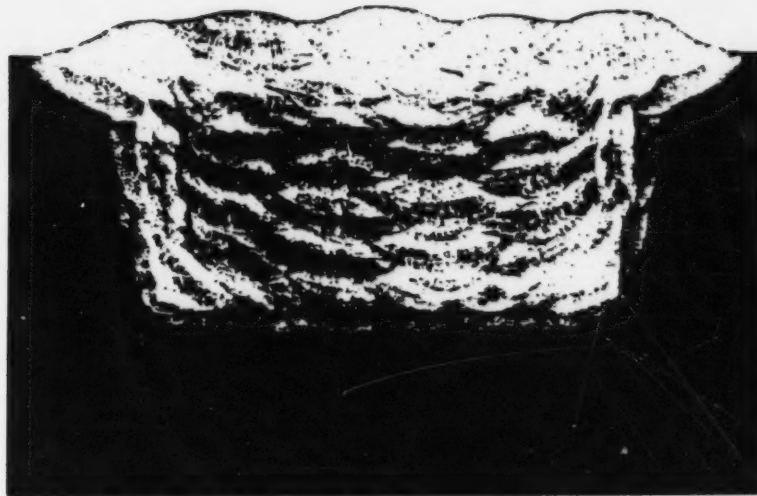
Procedure By:
Lorne Thompson



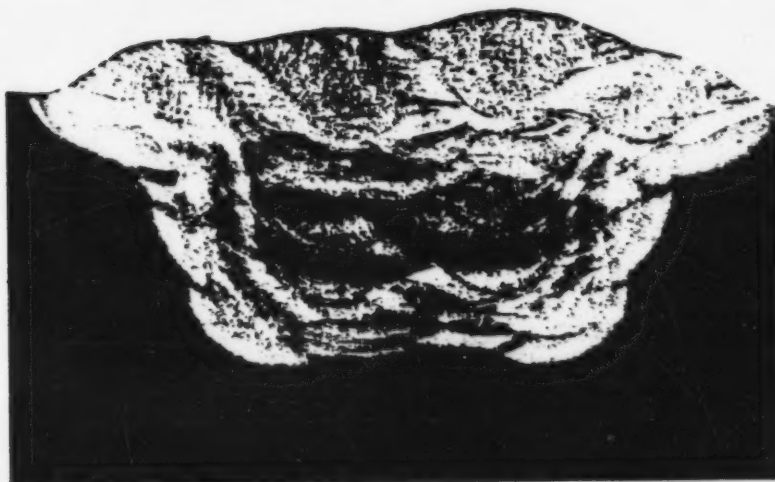
Sequence #3: Low Heat Input Temperbead Procedure (Panel I.D. 2SP1)
(Neg #12028) x 3



Sequence #3: High Heat Input Temperbead Procedure (Panel I.D. 2SP2)
(Neg# 12029) x 3



Sequence #4: Low Heat Input Procedure (Panel I.D. 2SQ1)
(Neg #12025) x 3



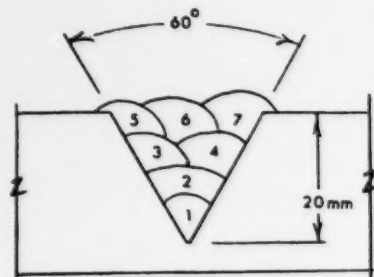
Sequence #4: High Heat Input Procedure (Panel I.D. 2SQ2)
(Neg# 12027) x 3

APPENDIX B

P-GMAW PROCEDURES AND PHOTOMACROGRAPHS

Material Specification: EH36 and EH36 Modified
Welding Process: Pulsed Gas Metal Arc Welding
Manual or Machine: Machine
Position of Welding: 1G (Flat position)
Filler Metal Brand Name: Various Dia. = 1.2 mm
Filler Metal Classification: See program matrix
Shielding Gas: C5 or C20 Flow Rate: 20-25 lpm
Nozzle Orifice Size: 16mm
Single or Multipass: Multipass
Single or Multiple Arc: Single
Heat Input Requirement (E): 2.0 kJ/mm
Preheat Temperature: Room Temperature (20°C)
Interpass Temperature: 100°C
Preheat Method: _____
Preparation: All grooves prepared by machining

(Indicate material thickness on drawing.)



Joint Preparation

[illegible]

Procedure Notes:

- ① The bead size and sequence was controlled ①
② by wire feed speed and travel speed. ②
③ Slight variations in current and voltage ③
④ were noticed which probably reflect the ④
⑤ effect of varying wire and gas compositions. ⑤
⑥ _____ ⑥
⑦ _____ ⑦

Procedure Application Notes:

- ① _____
- ② _____
- ③ _____
- ④ _____
- ⑤ _____
- ⑥ _____
- ⑦ _____

Date:

March 1990

Welder's Name:

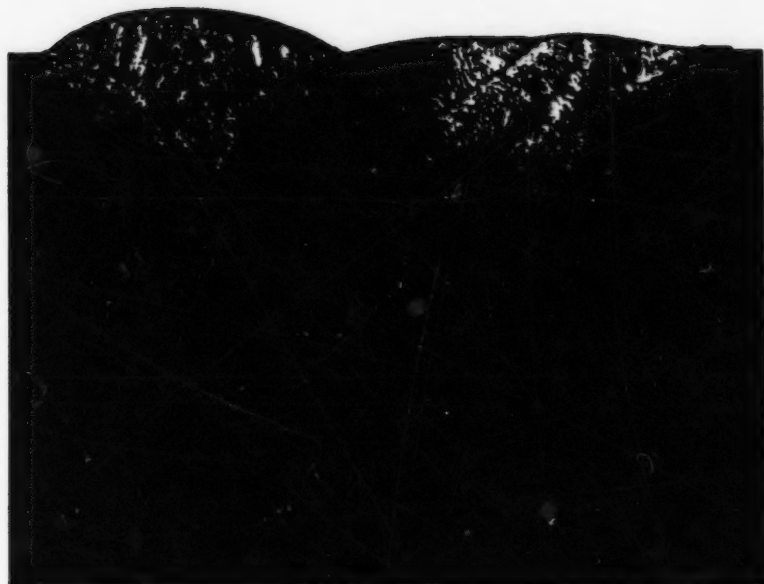
Charlie Daigle

Inspected By:

K.G. Morrison

Procedure By:

Charlie Daigle



P-GMAW Macrosection (Panel 2PAC5) neg# 12033, x 3